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A DFN Approach to Evaluating the Hydrogeological Significance of Lithostatic Unloading in Fractured Strata Around Open-Pit Workings

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ABSTRACT: The majority of open-pit mineral workings are established in hydrogeological environments in which unsaturated drainage or saturated groundwater flow occurs predominantly via discrete fracture networks. Stress relaxation resulting from open-pit mineral extraction can lead to a change in host rock fracture network configuration and fracture hydraulic properties, with the potential to change local hydrogeological characteristics and groundwater flow regimes. Research being undertaken at the University of Leeds is applying a DFN approach to investigate the hydrogeological significance of such effects in relation to methodologies for impact assessment at mineral sites. The paper presents a summary of the research approach and preliminary results. A discrete finite element approach to geomechanical modelling has been undertaken with simulation of DFN evolution in response to lithostatic unloading for a range of pre-existing discontinuity configurations, lithological types and variations in in-situ stress regimes. Preliminary modelling results have provided improved understanding of the vertical and lateral extent of potential DFN response for a range of excavation profiles. Research results will be used to define conditions under which open-pit mineral extraction could lead to hydrogeologically significant change in fracture flow drainage characteristics at a scale relevant to hydrogeological impact assessment for new and existing mineral workings.

1. INTRODUCTION

Hydrogeological impact assessment for new open-pit mineral development is invariably based on analysis using pre-development data sets. Characterization of potential external effects, using analytical or numerical modelling techniques, relies on the use of hydraulic parameters determined from pre-development investigation and testing with no account for potential change in hydraulic parameters as a consequence of lithostatic unloading associated with removal of mineral and overburden.

The concept of stress relaxation and the development of excavation damage zones (EDZ) and excavation disturbed zones (EdZ) around open pit mineral workings, as a consequence of mineral extraction, has been established for many years (Kalkani, 1977; Nichols, 1980; Seager, 1963; Stacey et al., 2003; Davies and Bernier, 2003). Many studies into the effects of stress relaxation around tunnels and underground mine entries (Aoyagi et al., 2014; Bai and Elsworth, 1994; Barton and Shen, 2017; Perras and Diederichs, 2016) have provided insight into the geomechanical response with regard to face stability, fracture propagation and associated groundwater seepage characteristics (Obeysekara et al., 2017; Tsang et al., 2005; Molinero et al., 2002), however, the majority of studies in open pit environments have tended focus primarily on excavation face stability (Stead et al., 2004) rather than site-scale aspects of damage and disturbance and the associated hydraulic implications.

The majority of open-pit mineral workings in hard rock environments are established in formations that tend to have low intergranular porosity and therefore groundwater drainage is dominated by secondary porosity systems associated with the presence of discontinuities in the rock mass. This assessment was reinforced by research undertaken as part of the Large Open Pit (LOP) project completed in 2009 (Beale and Read, 2014) which concluded: ‘Fracture flow conditions usually occur within most competent (consolidated) rock types, such as igneous, metamorphic, cemented clastic and carbonate rocks, and in consolidated coal formations. Although the unfractured rock may contain some pore space, this is mostly unconnected and much of the groundwater within these rocks occurs within fractures in the rock mass. Groundwater movement in these materials therefore occurs mostly by fracture flow and drainage from unfractured blocks will be effectively non-existent.’

Despite the prevalence of fracture flow systems in strata surrounding the majority of open-pit workings, most hydrogeological impact assessments are undertaken using an equivalent porous media (continuum) approach where groundwater flow in rock discontinuities is considered as a contribution to flow through the bulk rock mass rather than flow through discrete fracture systems (Digges La Touche and Cottrell, 2017; Rapantova et al., 2007). Continuum approaches can be justified where discontinuity scale and density promotes a hydraulic response that is comparable to porous media, particularly given the increased data requirements of more complex discrete fracture flow analysis (Domenico and Schwartz, 1998). However, such approaches do not adequately represent hydraulic conditions within fracture networks, preferential flow paths or fracture recharge-discharge relationships at excavation faces.

Improving the accuracy and reliability of hydrogeological assessment at open-pit mineral workings is dependent on an ability to define and conceptualise existing fracture flow systems and to understand any change that would result from mineral extraction. An understanding of fracture network change in response to lithostatic unloading is a key aspect of this process.

Relatively small changes in fracture aperture or fracture network connectivity can have a major effect on groundwater flow and contaminant transport through fractured strata (Lui and Elsworth, 1997). Recent work on joint stress-stiffness-aperture relationships is providing a basis for the development of new approaches to analysis of hydraulic capacity in relation to stress variation (Lei et al., 2017; Pyrak-Nolte and Nolte, 2016).

Research being undertaken at the University of Leeds is designed to investigate whether the physical change in hard rock joint or fracture networks, in response to lithostatic unloading as a consequence of mineral extraction, is hydrogeologically significant and, if so, under what conditions. The overriding aim of the research is to inform hydrogeological impact assessment methodologies for evaluation of new open pit mineral workings. More specifically the project aims to investigate the following:

(i) the scale and magnitude of fracture network change in response to reduction in gravitational loading in excavated areas for a range of representative lithologies;

(ii) the effect of fracture network change on fracture flow characteristics including development of preferential pathways, fracture connectivity and the transition from laminar to turbulent flow conditions;

(iii) the effect of fracture network change on the external impact of mineral workings on local hydrogeology, in comparison to current approaches to hydrogeological impact assessment.

This paper provides preliminary details of progress with item (i) and the implications for subsequent research aims.

2. APPROACH AND METHODOLOGY

To evaluate the hydrogeological significance of lithostatic unloading in fractured hard rock environments it is necessary to establish an understanding of fracture network response to stress relaxation. A discrete fracture network (DFN) modelling approach is being used to investigate fracture network response to stress relaxation in a number of representative extractive environments and configurations. Following a review of geomechanical modelling systems, Elfen software (Rockfield International) was selected for application to this research. The ability of Elfen to incorporate the full range of simulation from continuum to discontinuum conditions, allowing DFN evolution by new fracture propagation, was a determining factor in model selection.

From a hydrogeological perspective the two parameters of greatest interest are:

(i) DFN connectivity; and

(ii) Fracture aperture change

Changes in connectivity would occur in response to new fracture development or the opening of fractures that were previously closed and therefore not available for fluid flow. To support analysis of DFN connectivity, additional tools are required and FracMan software (Golder Associates) was selected for this purpose. FracMan provides a stochastic basis for the development of DFN's for application to geomechanical modelling in Elfen and provides a method for analysis of the effect of DFN connectivity change on the movement of groundwater following stress relaxation due to mineral extraction.

As the study is aimed at evaluating hydrogeological significance, rather than attempting to simulate conditions at any specific site, it would have been possible to develop DFN's from generic input data. However, to ensure that the modelling is as representative as possible of real world conditions, discontinuity data has been collected from several UK mineral sites. The field data collection programme has included site-based discontinuity mapping, borehole construction and geophysical logging.

Preliminary modelling work has been based on data obtained from Blaxter Quarry in Northumberland, UK (NGR NY932900). Blaxter Quarry is a small dimension stone quarry working a massive sandstone unit within the Carboniferous Tyne Limestone Formation. As shown in Figure 1, the sandstone incorporates well-defined orthogonal jointing and, as a dimension stone quarry, there has been limited use of explosives for mineral extraction which minimizes the extent to which excavation faces have been subject to blast damage.

Geophysical image logs from boreholes drilled at increasing distance from the excavation face have provided data on fracture intensity variation with distance for comparison with numerical modelling results.

Figure 1: Jointed massive sandstone at Blaxter Quarry.

Additional DFN data sets have been derived from mineral workings in the UK Carboniferous Limestone and Coal Measures Strata and will form the basis for future modelling work. Following application of DFN's based on site-specific measurement, FracMan will be used to produce distribution-based fracture networks for more generic simulation with Elfen.

Following the establishment of analytical procedures and preliminary results from the Blaxter Quarry datasets, geomechanical modelling work will be expanded to include consideration of a range of DFN configurations, lithology combinations, excavation depth and in-situ stress conditions. The results of geomechanical modelling will provide the input datasets for subsequent hydrogeological modelling aimed at evaluation of the potential effect of DFN change on groundwater flow patterns around open-pit workings.

3. PRELIMINARY MODEL DEVELOPMENT

Investigation of stress relaxation patterns, rock mass displacement and joint surface dilation has been undertaken through development of a series of finite-element geomechanical models using the Elfen modelling system. Excavation configuration and joint network characteristics have initially been based on field measurements from Blaxter Quarry. Modelling has initially been undertaken in two-dimensions (2D) on a representative extractive profile, but subsequent work will incorporate development of three-dimensional models to check 2D model sensitivity to section location and orientation.

The model incorporates the two lithologies found at Blaxter Quarry i.e. the massive jointed sandstone unit and the underlying limestone unit. On the basis of site-specific observation and measurement, bedding planes and the primary orthogonal joint set form the DFN, with joints extending through the full depth of the sandstone unit. The bedding planes have a consistent dip of 5° to the west with a strike of 340° and the principal joints dip at 85° with a strike of 260°. Bedding planes are included in the model with a fixed 5m spacing and the primary joints are included with a consistent 10m spacing. Horizontal bedding fractures at 10m vertical intervals were incorporated in the limestone unit. General model configuration is shown in Figure 2. The model is orientated approximately east-west along the bedding dip direction. Preliminary modelling was aimed at investigating effects around relatively shallow excavations of 30m to 60m below ground level with an excavation face angle of 70 degrees. The preliminary model domain was therefore established at 300m x 100m with an unstructured finite-element mesh size of 2m, to balance processing time with required data density. The model was subject to gravitational loading with a lateral in-situ stress ratio (k) of 0.27.

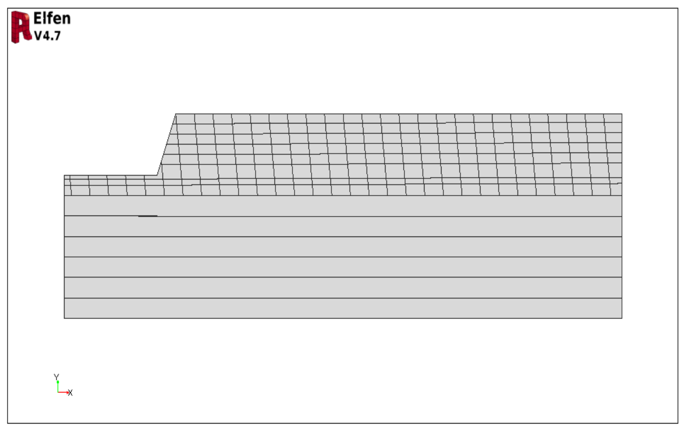

Figure 2: General model configuration (Domain 300m x 100m)

Geomechanical parameters applied to the sandstone and limestone units in the model, as presented in Table 1, were derived from published literature values for comparable strata in northern England (Bell, 1978; Bell and Culshaw, 1998).

Table 1: Model input parameters

Parameter	Value	Units
SANDSTONE		
Youngs modulus	22	GPa
Poisson ratio	0.211	-
Shear modulus	13.36	GPa
Density	2360	kg/m^3
Cohesion	2	MPa
Friction angle	40	Degree
Dilation angle	5	Degree
Tensile strength	2.5	MPa
Fracture energy	20	J/m^2
Joint normal stiffness	0.5	GPa/m
Joint tangential stiffness	0.05	GPa/m

Joint friction ratio (tan ϕ)	0.55	-
Joint cohesion	0.01	MPa
LIMESTONE		
Youngs modulus	30	GPa
Poisson ratio	0.20	-
Shear modulus	15	GPa
Density	2660	kg/m^3
Cohesion	9	MPa
Friction angle	40	Degree
Dilation angle	5	Degree
Tensile strength	3.8	MPa
Fracture energy	19.5	J/m^2
Joint normal stiffness	1.0	GPa/m
Joint tangential stiffness	0.1	GPa/m
Joint friction ratio (tan ϕ)	0.55	-
Joint cohesion	0.1	MPa

Lithology specific data was applied to the limestone unit in the model and the sandstone bedding plane tangential stiffness was increased from 0.05 GPa to 0.1 GPa to represent the effects of infill on some bedding planes.

The model was configured with displacement constrained in a vertical direction at the model base and in a horizontal direction at the vertical model boundaries, excluding the excavation face. For this preliminary analysis, the model was established with two-stages to represent (i) geostatic initialization, and (ii) excavation. Model displacements were reinitialized prior to commencement of the excavation stage.

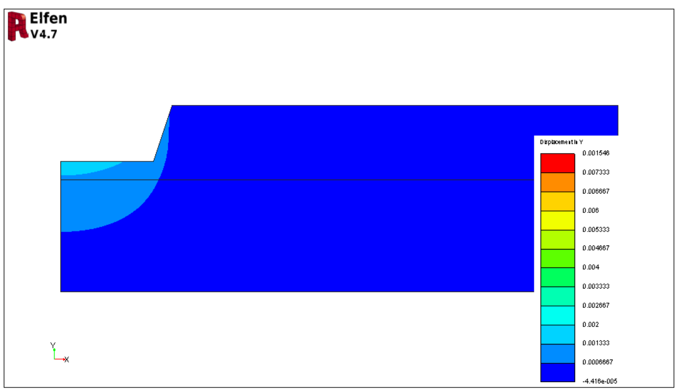

Figure 3: Vertical displacement (m) with no DFN (+ve upward)

To provide a basis to evaluate the effect of joint systems on host strata deformation, and to test boundary conditions, the model was initially run without a DFN. The results demonstrated the development of a disturbed zone around the excavation with the rock mass displacement beneath the excavation floor and behind the excavation face as expected. An example of model output showing vertical displacement post-excavation is presented as Figure 3.

With no fracture network, the model indicates maximum vertical displacement at the excavation floor of 1.5mm with definable displacement of >0.1mm at a distance of approximately 60m below the floor and 50m behind the excavation face i.e. approximately twice the depth of excavation.

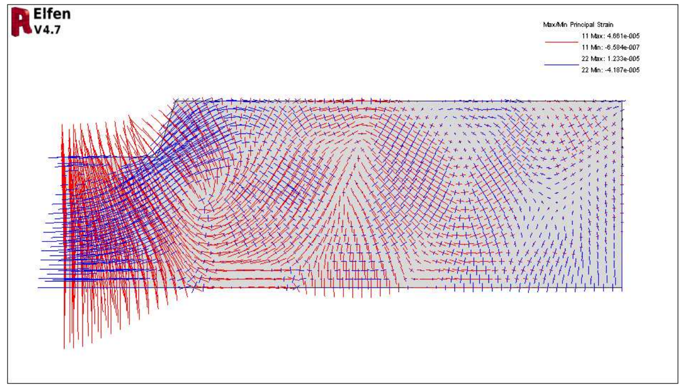

Figure 4: Principal stress distribution with no DFN

Analysis of the stress regime around the excavation indicated vertical stress relaxation at the excavation floor of 0.65 MPa pre-excavation to 0.095 MPa post-excavation. At the excavation face the horizontal stress reduced from 0.25 MPa pre-excavation to 0.056 MPa post-excavation. When compared to the specified sandstone tensile strength of 2.5 MPa it is apparent that, as indicated by modelling results, stress relaxation conditions are not consistent with new fracture development at such shallow excavation depth. The maximum and minimum principal stress distribution around the excavation is indicated in Figure 4.

Model results suggest the presence of boundary effects, particularly beneath the excavation floor, and hence further modelling work will require increase in model domain dimensions and review of the boundary conditions applied.

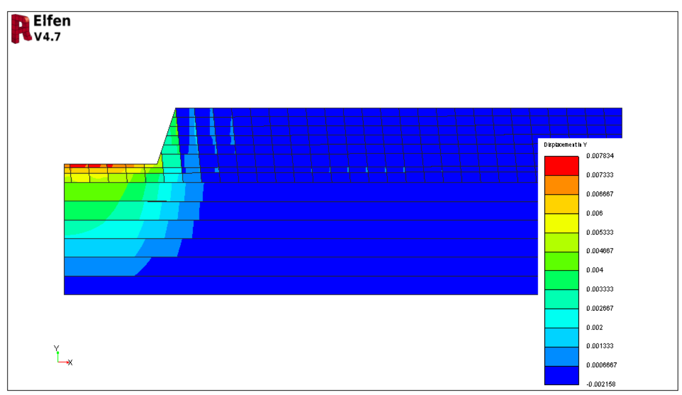

Figure 5: Vertical displacment (m) with DFN (+ve upward)

The introduction of the DFN to the model resulted in a change to the magnitude and extent of the post-excavation deformation zone. As shown in Figure 5, the presence of bedding planes and principal joints has a significant effect on vertical displacement with apparent slippage on discontinuities acting to accentuate rock mass displacement. The orientation of the DFN in this model ensures that displacement occurs both as a consequence of intact rock strain and movement across bedding/joint surfaces.

Rock mass displacement results for vertical and horizontal model node transects have been extracted for strata beneath the excavation floor and behind the excavation face. The results are presented graphically in Figures 6 and 7.

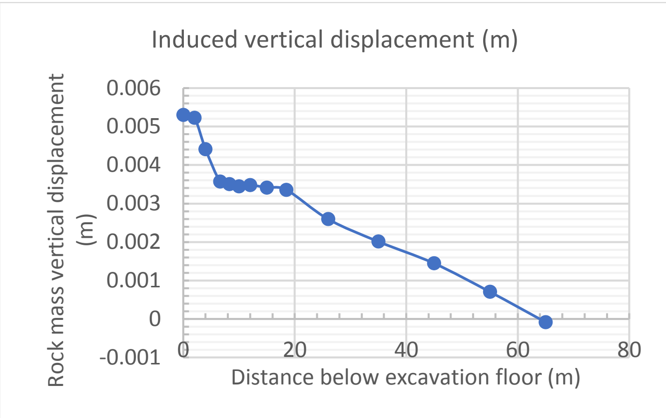

Figure 6: Vertical displacement beneath excavation floor (+ve upwards)

With the DFN present in the model the maximum displacement at the excavation floor is approximately 5.3mm, reducing at an approximately linear rate towards the lower model boundary. The introduction of the fracture network has therefore resulted in an increase in upwards excavation floor displacement from 1.5mm to 5.3mm.

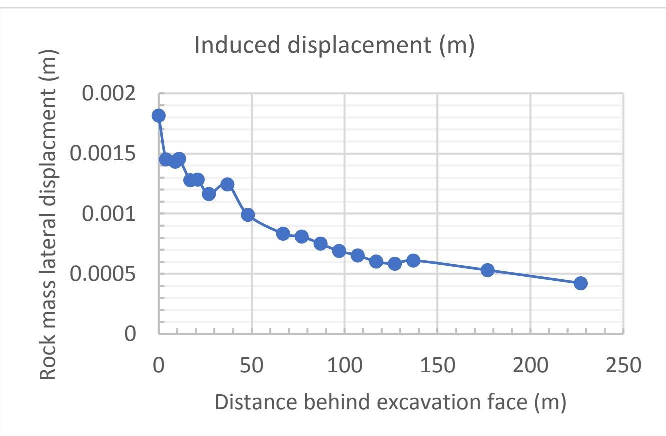

Figure 7: Lateral displacement behind quarry face.

Similar analysis indicates a maximum lateral displacement of 1.8mm at the excavation face (movement into the excavation) compared to a maximum displacement of 0.3mm without the fracture network. As shown in Figure 7, rock mass lateral displacement with the DFN reduces asymptotically with increasing distance from the excavation face, reaching a value of approximately 0.5mm at a distance of around 125m.

Hence, the preliminary model results indicate that rock mass displacement due to stress relaxation increases in both magnitude and vertical/lateral extent when discontinuities are present, suggesting the model is functioning as expected.

One of the key objectives of geomechanical modelling is to investigate joint aperture change as a consequence of stress relaxation. Several recent studies have progressed development of analytical relationships between stress, joint stiffness and joint aperture (Lei et al., 2017; Pyrak-Nolte and Nolte, 2016).

Elfen uses a 'penalty' parameter to represent joint stiffness. Joints are represented in the model as straight lines with no width, however, the software incorporates a stress-penalty-penetration relationship which relates the position of finite elements representing joint surfaces in relation to applied stress and predefined joint stiffness. The penalty function is in fact a specific joint or fracture stiffness with units (Pa/m). A change in element penetration can be interpreted as a change in the relative position of joint surfaces, and hence in an unloading environment, as induced joint surface dilation. As indicated in Table 1, a normal joint stiffness of 0.5 GPa has been applied to both the principal joints and the bedding. This value has been derived from review of previous studies (Morris et al., 2017) indicating that for a normal stress of 1 MPa and continuous joints or bedding of several tens of metres, as modelled, joint stiffness may fall in the range of 0.5 GPa to 1.5 GPa depending on joint length.

Analysis of joint surface dilation has been undertaken for the same excavation floor and face transects that were used to investigate rock mass displacement. Penetration changes normal to joint or bedding surfaces have been extracted from the model to provide an indication of relative movement in response to stress change. [The results are not related to any initial aperture.] Subsequent analysis will be undertaken to investigate relationships between joint surface dilation and aperture change.

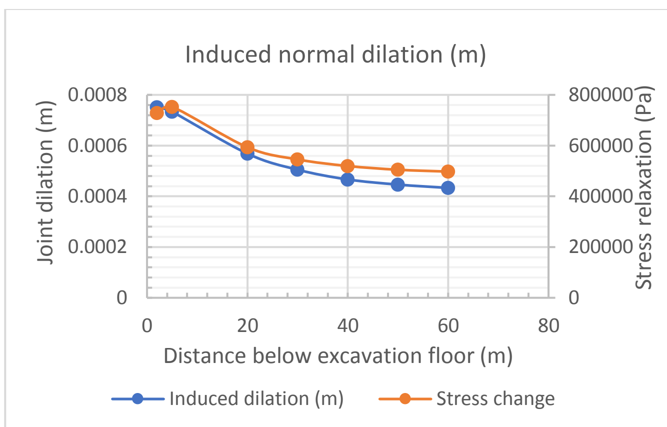

Figure 8: Normal joint dilation below the excavation floor.

The results of joint surface dilation analysis below the excavation floor are presented in Figure 8. The maximum dilation of 0.75mm occurs on the bedding fracture closest to the excavation floor with progressive reduction at increasing depth to approximately 0.4mm at 60m. Figure 8 also shows the change in vertical stress at each joint location confirming close correlation between stress relaxation and joint surface dilation. The maximum stress change on the bedding fracture closest to the excavation floor is 0.73MPa reducing from an initial pre-excavation value of 0.82MPa to a post excavation value of 0.091MPa.

As movement occurs on individual joint surfaces, the total displacement across the joint system at the excavation floor is the sum of all individual joint movements. In the modelled example the sum of joint movement at the excavation floor is 3.9mm. When compared to the maximum rock mass displacement at the excavation floor of 5.3mm it is apparent that joint surface dilation in response to unloading accounts for approximately 75% of total vertical displacement.

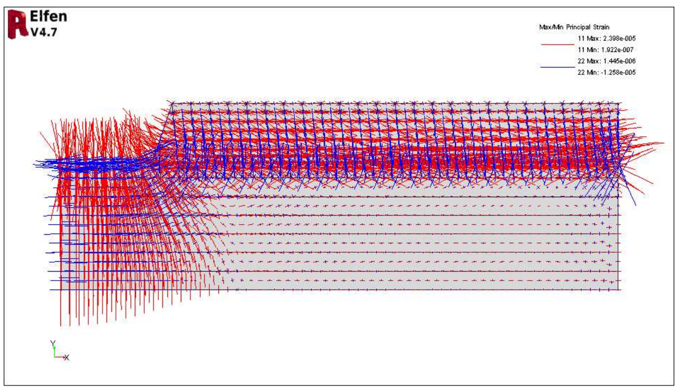

Figure 9: Principal strain results

In the modelled example, simulation results suggest that displacement on the excavation floor is largely due to dilation of existing discontinuities rather than extensional strain of the intact rock. Maximum and minimum principal strain results for the model including the DFN are shown in Figure 9. The results are consistent with the above analysis and indicate small maximum values of 2.4e-05 m at the excavation floor.

Repeating the same analysis with regard to lateral joint surface dilation behind the excavation face results in much lower joint dilation values with a maximum of 0.1mm at the joint closest to the excavation face and a combined total movement on all joint surfaces of 0.33mm. The maximum lateral displacement of the face into the excavation is 1.8mm, so joint surface dilation equates to approximately 18% of the total lateral displacement.

Further model development is underway to investigate the effects of lithological variation, excavation depth, DFN configuration and in-situ stress conditions on model outcomes. Preliminary sensitivity analysis, for this particular model, has indicated that model results are less sensitive to variation in material properties and in-situ stress conditions but more sensitive to variation in joint stiffness.

4. POTENTIAL HYDROGEOLOGICAL SIGNIFICANCE

Preliminary DFN modelling has indicated that lithostatic unloading as a consequence of mineral extraction could lead to joint surface dilation, and hence potentially to changes in fracture aperture/hydraulic capacity, over a significant distance from the excavation floor and face. From the perspective of hydrogeological impact assessment, discontinuity system evolution in response to lithostatic unloading may be significant in relation to the following;

- the areal extent of hydrogeological impacts outside the excavation boundary resulting from excavation dewatering or drainage,
- hydraulic gradient reduction with implications for groundwater flow and groundwater pore pressures,
- transient groundwater response to recharge,
- surface infiltration and effects on soil water and shallow hydrological features, and
- capacity for contaminant transport.

If fracture system evolution leads to an increase in rock mass permeability, the radius of impact on groundwater systems around an excavation could be greater than pre-development prediction. Alternatively, enhanced fracture connection with surface recharge sources may lead to increased recharge that would tend to reduce the radial distance over which impacts on groundwater levels are experienced.

Higher fracture system permeability is unlikely to have a major impact on the rate of groundwater flow into open pit excavations as flow rates may be limited by lower hydraulic gradients and a tendency to non-laminar flow conditions near excavation boundaries (Dudgeon, 1985). However, any significant change in groundwater pressures would have implications for slope stability and slope depressurisation (Beale and Read, 2014; Marchand et al., 2010).

Previous studies have indicated that greatest extensional strain may occur at shallow depth in the upper faces of an excavation with enhanced development of sub-vertical fractures behind the excavation face (Jaeger et al., 2009). Depending on the presence and hydraulic properties of any overburden present, enhanced near surface fracturing may lead to enhanced infiltration capacity with increased groundwater recharge. Enhanced infiltration could have an impact on soil water content or the resource available to any water dependent features within the area of influence of mineral development. Such effects could occur whether the excavation is above or below the water table.

As previously reported in other studies (Stacey et al., 2003), preliminary analysis of principal stress orientation in this model indicates that if excavation damage resulted in the formation of new fractures due to extensional strain effects i.e. with weaker rock or greater depth of excavation than currently modelled, any new fractures would tend to be sub-parallel to the excavation face and floor, subject to any other geological constraints. New fracture system geometry would therefore tend to promote development of flow paths around and under mineral excavations with higher permeability than pre-development. As a consequence, there may be enhanced capacity for migration of contaminants associated with mineral development or present in the host environment, with potential implications for groundwater quality, during both the operational phase of development and post restoration.

The hydrogeological significance of such DFN changes will vary for different lithological regimes, depth of extraction and prevailing hydrogeological conditions. The results of DFN modelling will be used to draw conclusions regarding the hydrogeological significance of geomechanical response to mineral extraction with the aim of providing guidance on the inclusion of such effects in hydrogeological impact assessment for new mineral development, where it is appropriate.

5. PRELIMINARY CONCLUSIONS

Preliminary DFN modelling results have demonstrated that stress relaxation associated with lithostatic unloading at open-pit excavations could have a significant effect on local hydrogeological conditions. Subject to further research, preliminary work has indicated that:

(i) Even at shallow depth, lithostatic unloading could lead to fracture network change over significant vertical and lateral distance;

(ii) The presence of pre-existing discontinuities may increase the magnitude and extent of post-excavation disturbance;

(iii) Dilation of pre-existing discontinuities may account for the majority of displacement beneath the excavation floor;

Further work will enhance and test these preliminary conclusions in relation to a wide range of geotechnical conditions.

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